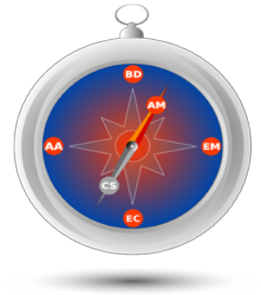




Development Of Algorithms For Simulation Of Electron Cloud Diagnostics For Project X

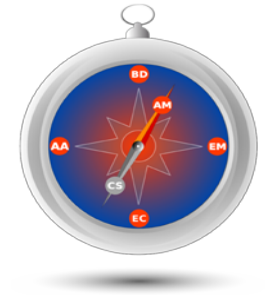


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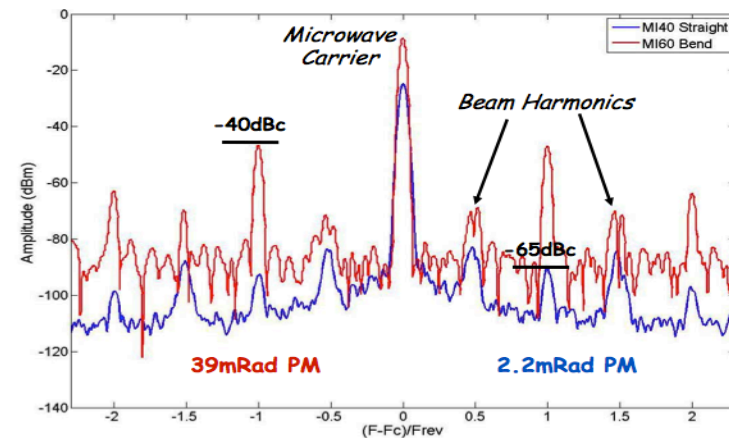
September 28, 2012

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Electron Clouds Can Limit Accelerator Performance

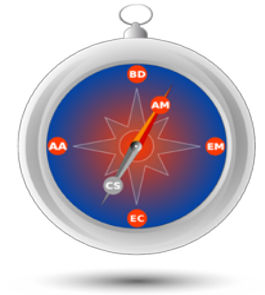


- Low density electron plasmas can form in circular accelerators via synchrotron radiation or stray beam particles striking beam pipe walls
- Primary electrons are accelerated by subsequent beam bunches which then create secondary electrons
- Although the plasma is low density ($\sim 10^{11} - 10^{15} \text{ e}^-/\text{m}^3$), they can cause beam instabilities that limit accelerator performance
- This is especially a concern for new high-performance accelerators such as the ILC and Project X
- Electron clouds are modulated on a revolution timescale by gaps in the bunch train, where the plasma dissipates to the walls
- Travelling wave rf diagnostics can measure time-averaged cloud densities by detecting this modulation
- In real life, experiments measure side bands due to plasma modulation, with a height that depends on the average plasma density



N. Eddy, Project X Collab. Meeting 2009

Travelling Wave rf Diagnostics Can In Theory Measure Electron Plasma Density



- Phase shifts are theoretically linearly dependent on plasma density (for uniform density plasmas with no ambient magnetic fields)

$$\Delta\phi / \ell = \frac{\pi}{c} \frac{f_p^2}{\sqrt{f^2 - f_{co}^2}}$$

- In spectral measurements, the side band amplitude is also linearly related to the plasma density

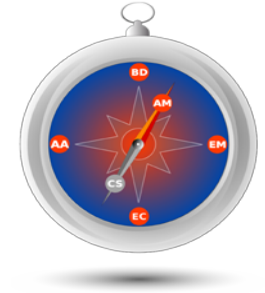
$$\frac{A_s}{A_c} = \frac{\pi}{2} \frac{n_e}{n_{crit}} \frac{L}{\lambda_0} \frac{\lambda}{\lambda_0}$$

$$\omega_{carrier}^2 = \frac{e^2 n_{crit}}{m_e \epsilon_0} \cong 3181 n_{crit}$$

$$\lambda_0 = \frac{c}{f} \quad \lambda = \frac{c}{\sqrt{f^2 - f_c^2}}$$

- However, other factors complicate the relationship between phase shift measurements and actual plasma density
- Numerical modeling of traveling wave rf diagnostics can provide a way to interpret measurements and better estimate electron cloud densities

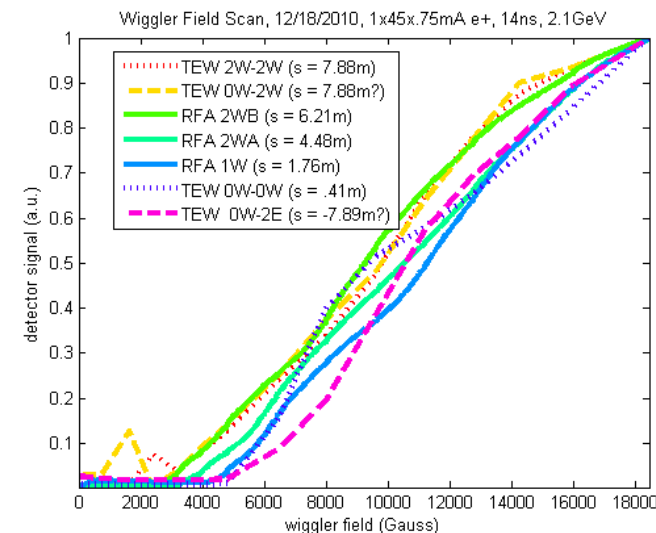
In Practice, It Is Not Known How To Get Plasma Density From Only Side Band Signals



- Spectral signals depend not just on cloud density, but also amplitude changes (generally thought to be small), path length through the cloud (often unknown), spatial distribution of electrons (time-dependent), and magnetic field configuration
- Phase shifts (linear approximation, no B field):

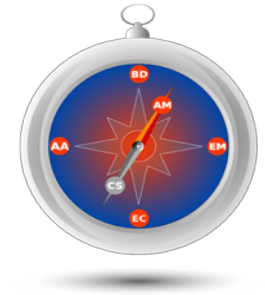
$$\Delta\phi / \ell = \frac{\pi}{c} \frac{f_p^2}{\sqrt{f^2 - f_{co}^2}}$$

$$f_p \approx 8990 \sqrt{n_e} \cdot 10^{-6} \text{ MKS}$$

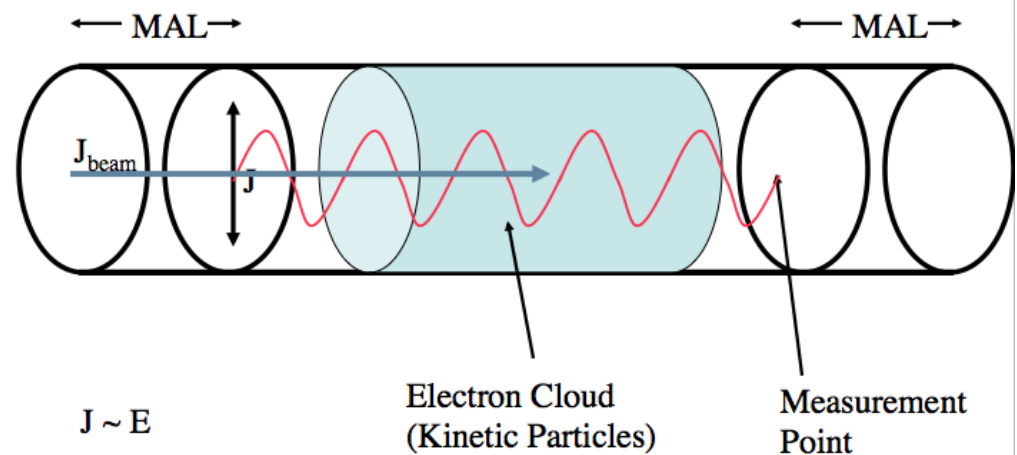


- Accurate simulations are able to model both cloud build up, and microwave transmission diagnostics
- Reproducing spectra requires very long simulations in order to resolve modulation frequencies (hundreds of kHz to tens of MHz)
- Determining phase shift effects for different model parameterizations (cloud density, magnetic field configuration, etc) is more manageable

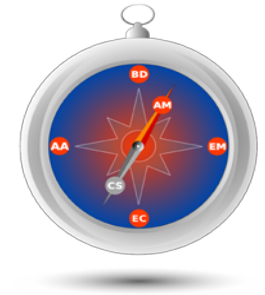
Traditional PIC Algorithms Can Not Reproduce Diagnostic Spectra



- Previous Vorpil simulations of traveling wave rf diagnostics contained a current source to launch rf into the plasma, and either PMLs or MALs to absorb rf at the ends of the wave guide
 - This produced a fair amount of broadband noise due to the finite extent of the current source
- Self-consistent kinetic particles provided estimates of phase shifts
- Cloud build up simulations have also been extensively performed using POSINST, Warp, Vorpil, and other simulation codes
 - It is important to use kinetic particles in build up simulations in order to capture wall effects (SEY) and cloud evolution due to beam passages
- However, for modeling rf diagnostics it is the dielectric properties of the plasma that are important
- Long time-scale simulations are needed to simultaneously resolve both rf scales and cloud modulations scales needed to reproduce spectra



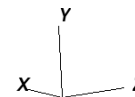
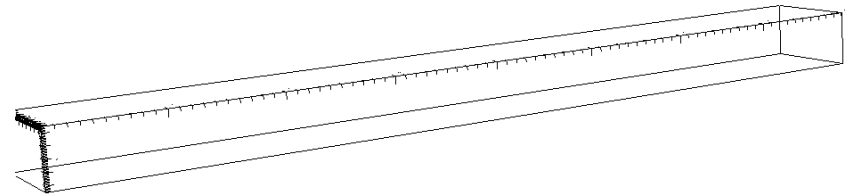
New Algorithms Improve Simulation Speed, Accuracy, and Efficiency



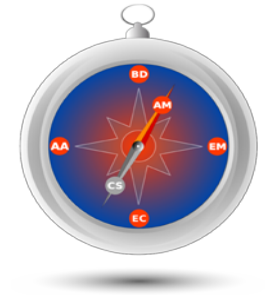
- (1) New port boundary conditions absorb a single dominant frequency, and can simultaneously launch a wave into the domain
- (2) We use a new plasma dielectric model for the electron plasma instead of kinetic PIC particles (**field updates only!**)
 - This eliminates so-called “particle noise” that arises from interpolation of particle charge and currents to the grid
 - Plasma dielectric model is faster than traditional PIC, because particle pushes are expensive
 - This reduces disk requirements because no particle dump files are produced
 - Does not address evolution of cloud density due to non-uniform magnetic fields
- (3) Low-frequency harmonic modulation of the dielectric tensor simulates cloud dissipation, and produces side bands

DB: jwdiel01-undamped_edgeE_0.h5
Cycle: 0 Time: 0

Vector
Var: vectorE
1200.0
900.0
600.0
300.0
0.000
Max: 0.000
Min: 0.000

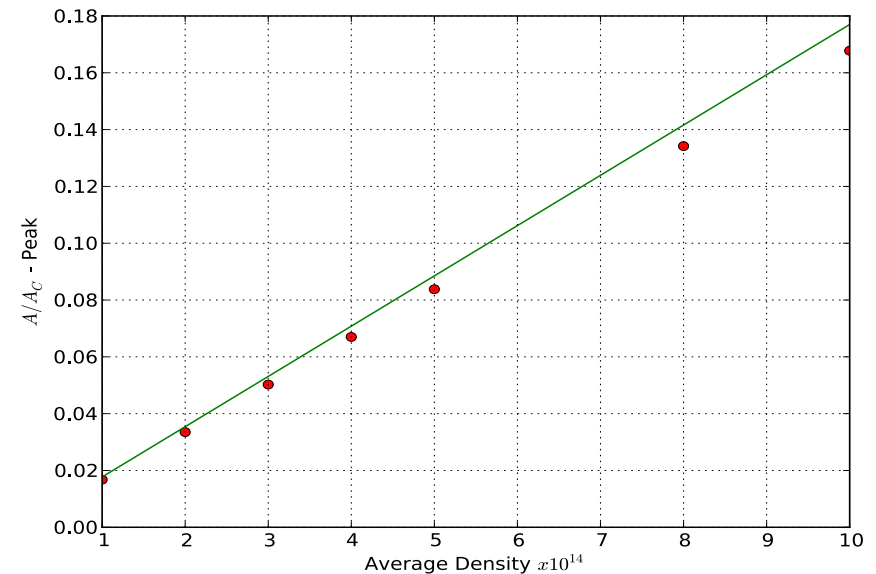
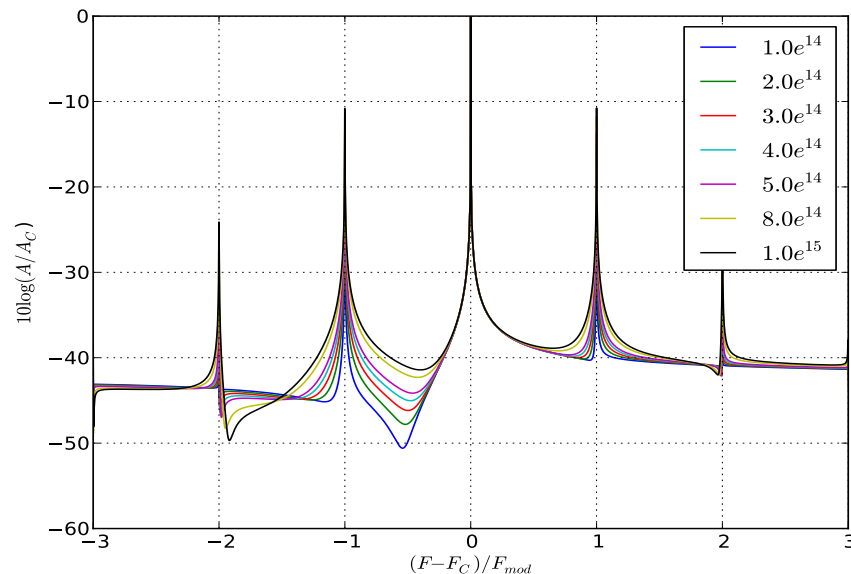


Results: Uniform Density Modulated Plasma Dielectric

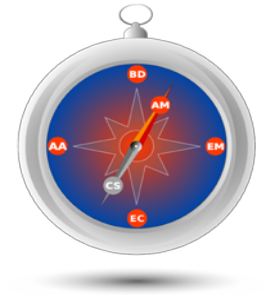


- 2-Dimensional Simulations (256x8)
- $f_{co} = 2.5$ GHz
- $f = 2.75$ GHz
- $dt = 5.8 \times 10^{-12}$
- 100,000 rf cycles (6,233,448 steps)
- 36.39 μs total simulation time
- $f_{mod} = 10$ MHz (~ 365 revolution periods)
- About 2 hours/run on 16 processors

- Simulations are very stable over long time scales
- Side bands are well resolved
- Side band amplitudes are linear with plasma density, as expected
- There are small systematic errors compared to theoretical values

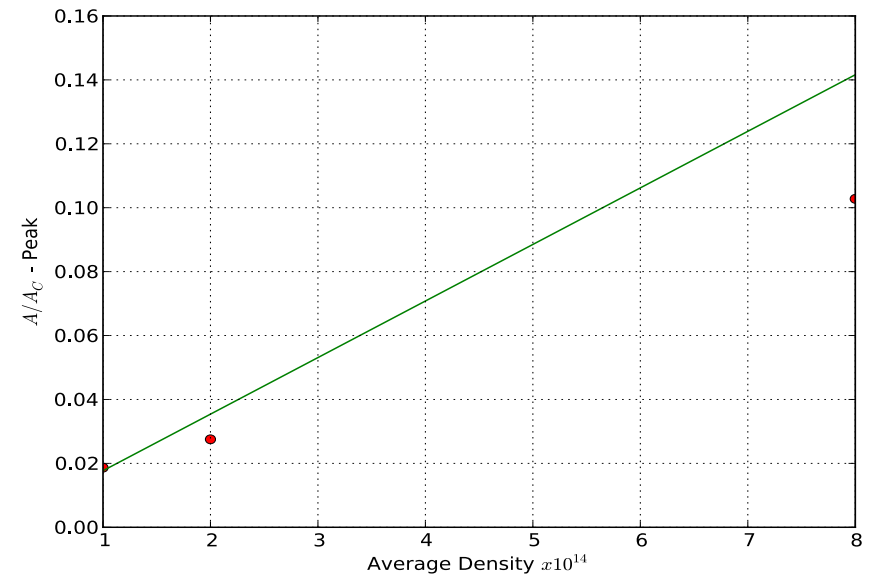
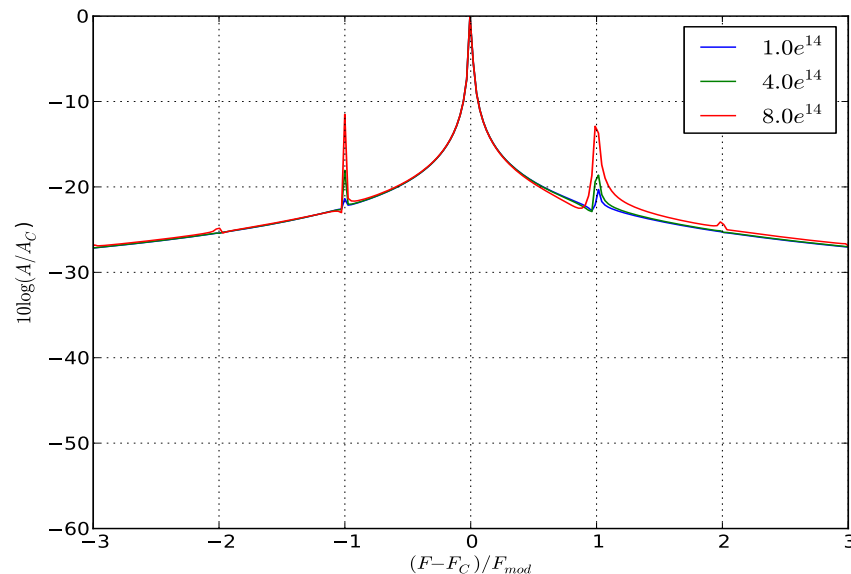


Results: Uniform Density Modulated Plasma Dielectric – Low Frequency Modulation

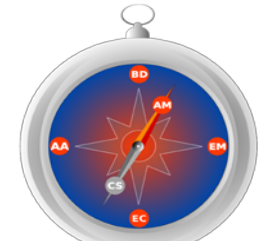


- 2-Dimensional Simulations (256x8)
- $f_{co} = 2.5$ GHz
- $f = 2.75$ GHz
- $dt = 5.8 \times 10^{-12}$
- 460,000 rf cycles (28,673,825 steps)
- 36.39 μs total simulation time
- $f_{mod} = 390$ kHz (~64 revolution periods)
- FFT on 2^{24} data points

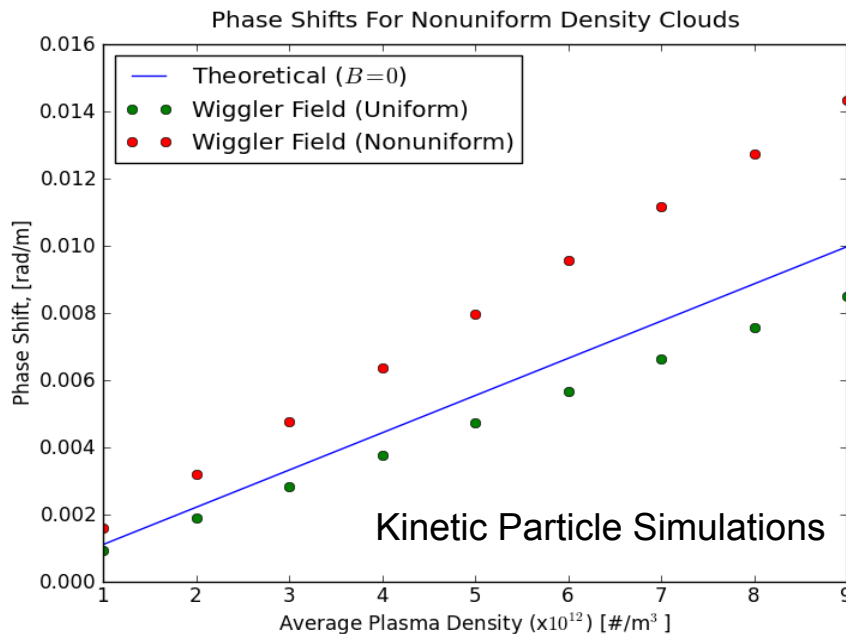
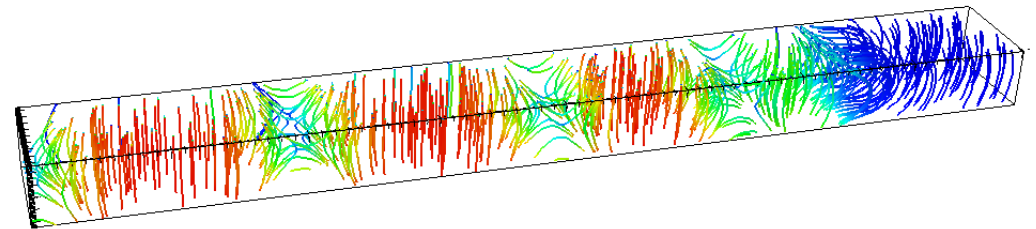
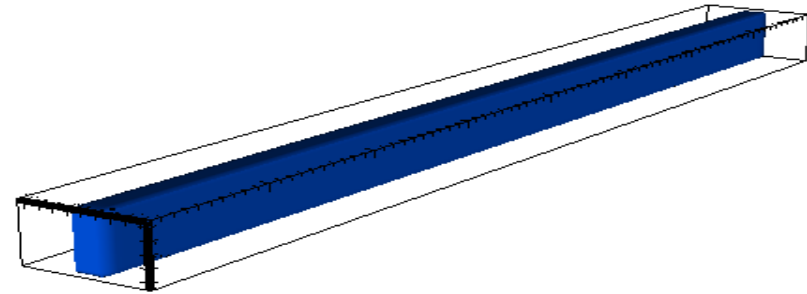
- Simulations are very stable over long time scales
- Side bands are not well resolved
- Modulation frequency does not appear in the theoretical expression for phase shift, but numerically it is very important
- Systematic errors are due to not resolving side band peaks well



Results: Magnetic Fields and Non-Uniform Density Clouds Have a Significant Effect on Induced Phase Shifts



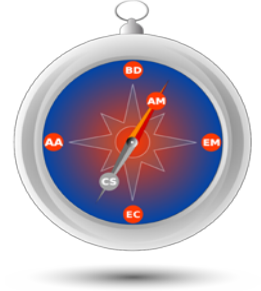
- 3-Dimensional Simulations (256x8x8)
- Reduce volume of plasma dielectric, but increase the dielectric strength, so overall equivalent density is the same
- Also added a highly non-uniform magnetic field (CESR wiggler) – dielectric tensor



Modulated dielectric simulations are still in progress.

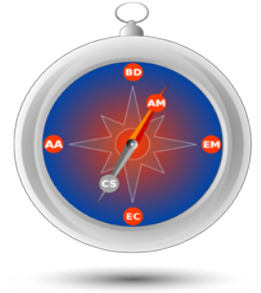
- Fields are stable and accurate at dielectric boundaries
- Simulations take a long time, but don't require a lot of processes
- Currently fighting with hardware and PBS issues

Future Plans Year 1: Verify Modulated Plasma Dielectric Model



- Quantitative comparisons between modulated plasma dielectric model and equivalent kinetic PIC models
 - Spatially variable plasma density
 - Plasma density changing in time (per kinetic buildup simulations)
 - rf propagation without beam current
 - Embedded boundaries
 - Error estimation and comparison between kinetic PIC and modulated plasma density models
 - Sensitivity study on density vs. side band height

Future Plans Year 1: Model Lossy Cavities With Dielectrics

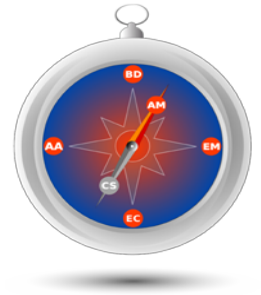


- We need to understand the effects of reflections and attenuation on plasma-induced phase shifts
- Model tabletop experiments at FNAL (Charles Tobin)
- Additional numerical models have been developed at Cornell for travelling wave diagnostics at CESR-TA, and we will support these experiments and modeling efforts
- Seek to quantify the effects of *not smooth beam pipes* on rf characteristics and side band heights



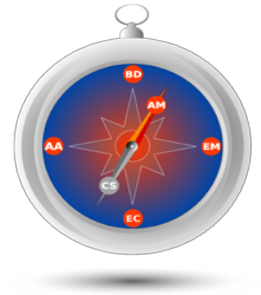


Future Plans Year 1: Support For FNAL Electron Cloud Simulations



- Continued support for numerical modeling of electron clouds at FNAL (Lebrun)
- Recent work includes:
 - Benchmarking Vorpil with POSINST in cloud buildup simulations (2D electrostatic)
 - Simulating buildup under different magnetic configurations (drift, dipole, and quadrupole) (3D electromagnetic)
- Current work:
 - Modeling of RFA diagnostics to measure electron cloud densities
 - Nearly complete

Future Plans Years 2 and 3:



- Year 2:
 - Develop and perform detailed simulations of resonant cavity rf experiments in the Main Injector using modulated plasma dielectric models of electron clouds using Vorpil. Simulation predictions of frequency shifts and side band measurements will be compared with experimental data to derive experimental electron cloud densities
- Year 3:
 - Develop and perform simulations of travelling wave rf diagnostics on meter spatial scales, but with detailed representations of beam pipe geometries and spatially variable magnetic fields. Modulated plasma dielectric models will be used to generate synthetic spectra to derive electron cloud densities in experimental data
 - Develop and perform simulations of travelling wave rf diagnostics over tens of meters of realistic Main Injector beam pipe including the effects of rf reflections and attenuation, spatially variable magnetic field configurations, temporal and spatial evolution of cloud densities, and plasma modulation at beam revolution frequencies